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Integrated technologies to enhance meat quality – An Australasian perspective

N.J. Simmons [a,*], C.C. Daly [a], C.R. Mudford [b], I. Richards [c], G. Jarvis [d], H. Pleiter [c]

[a] *AgResearch Ruakura MIRINZ Centre, East Street, Private Bag 3123, Hamilton, New Zealand*
[b] *Realcold Milmech Ltd., P.O. Box 4435, Eight Mile Plains, Qld 4113, Australia*
[c] *Meat and Livestock Australia, 23 Kyabra Street, Newstead, Qld 4006, Australia*
[d] *Meat and Wool New Zealand, 113-119 The Terrace, P.O. Box 121, Wellington, New Zealand*

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Abstract

Ensuring meat quality attributes meet the requirements of the diverse range of markets is a critical component for the continued success of the New Zealand and Australian meat industries. Developing cost-effective and flexible technologies to help meet this requirement is a central objective of a current Meat and Wool New Zealand and Meat and Livestock Australia funded programme. This initiative was developed three years ago; it is a collaborative programme that involves meat scientists, electrical engineers and commercial meat processors.

To ensure this programme successfully delivers technologies and knowledge to the Australasian meat industry, the following strategies have been developed: measurement of meat quality attributes 'on-line' during processing; development of 'expert systems' that can integrate and interpret on-line measurements and development of quality-related feedback systems from the market that can be fed back to producers; and, development of methods to manipulate structural and biochemical events in meat to create new commercial opportunities for both producers and processors.

This paper gives an overview of some of the new technologies that have developed from this programme that are being used commercially or, are undergoing the final stages of commercial validation.

Keywords: pH fall; Carcass chilling; Stimulation; Immobilisation; Electrical stunning; Hot-boning; Meat quality

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1. Introduction

The processing of animals into meat is recognised as having a significant influence on the quality attributes of meat. Meat processing, as defined in this paper, encompasses the procedures that start with slaughter and ends with post-rigor meat in a chilled state. This end condition produces a stable biochemical state in meat, although some important changes still continue albeit more slowly, particularly the proteolytic events important for tenderisation. Nevertheless, the early stages in carcass processing that follow soon after slaughter are far more dynamic and have greater implications for meat quality: not only are biochemical processes accelerated by the high carcass temperatures, but profound biochemical and structural changes are associated with the transformation of muscle tissue from the pre-rigor to the post-rigor states. These transformations have critical implications for the quality attributes of meat, and identifying appropriate processing conditions that manage quality in a cost-effective manner are important to commercial meat processing operations.

New Zealand meat particularly is presented to a number of diverse markets, and while the basic meat quality attributes required by the customers in these markets may be similar, the distance and time taken to reach them will be very different and these logistical issues may have the

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[*] Corresponding author. Tel.: +64 7 8271890.
E-mail address: nicola.simmons@carnetech.co.nz (N.J. Simmons).

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potential to adversely affect meat quality. However, studies during the last few years have demonstrated that, if processing is manipulated to allow for the subsequent differences in the transport and distribution chain, then the product attributes can be optimal for each of the markets. For example, the New Zealand meat industry has pioneered long storage periods for chilled lamb and beef to supplement the more traditional frozen products, but the optimum processing conditions are very different for chilled compared with frozen meats: chilled meats need to be processed for maximum stability, to slow biochemical processes and so maximise storage life; this contrasts with the requirement in frozen meat where the objective is to accelerate the post-mortem changes in order to reach acceptable quality standards before the stasis of the frozen state.

The two main determinants in defining the pre-rigor conditions are the rate of pH fall and the rate of cooling (Simmons, Auld, Thomson, Cairney, & Daly, 2000). These two variables are obviously not independent as temperature will affect pH fall, but pH fall can also be manipulated independently by the level of electrical inputs applied to the carcass. Electrical inputs that should be considered range from electrical stunning, used to either kill the animal or render it unconscious prior to neck cutting, to the various forms of electrical immobilisation and stimulation that occur during and after the dressing procedures. Even electrical inputs used to stiffen the carcass during hide pulling need to be considered.

Although these variables have long been recognised as important in meat processing, this review will consider more recent concepts and technologies that can potentially offer greater levels of control of these processing variables and thus provide new opportunities in meat processing.

2. The importance of managing pH and temperature decline

Historically, the interaction between chilling rate and pH decline was identified in the phenomena of cold shortening and PSE (pale, soft and exudative) meat. These represent the two extremes of the spectrum of pre-rigor pH/temperature histories: cold shortening is produced from the coincidence of low muscle temperatures while muscle pH is still high, which triggers severe muscle contracture (Locker & Hagyard, 1963), and these contractures cause meat to become both toughened and, in severe cases, prevent tenderisation during ageing (Davey & Gilbert, 1973). The converse of this is produced when very slow cooling is combined with high levels of electrical stimulation to give a low muscle pH combined with high muscle temperatures. This condition generates a range of adverse quality attributes, most notably denaturation of muscle proteins that gives rise to the pale colour and low water binding capacity associated with the PSE syndrome. The PSE condition can produce similar levels of shortening to cold shortening (Pike, Ringkob, Beekman, Koh, & Gerthoffer, 1993), giving rise to the term heat or rigor shortening, but this condition produces effects on toughening that are more complex and poorly understood when compared to cold shortening. The effects of rigor shortening on shear force values (measured objectively) are smaller and less inconsistent when compared with an equivalent shortening produced by low temperatures (Locker & Daines, 1976). In contrast, sensory panel assessments of rigor-shortened meat have shown significant increases in toughness, although the toughening does not match that of cold shortening (Hertzman, Olsson, & Tornberg, 1993). While the term PSE is typically associated with pork processing because of the high rate of glycolysis in some breeds of pigs, this condition can be seen in both beef and lamb cuts that have been subjected to high levels of electrical stimulation combined with slow chilling regimes.

Demonstrably, therefore, the pre-rigor temperature/pH environment ultimately determines the quality attributes of tenderness, texture, colour and colour stability, and purge losses. Although cold shortening and PSE represent the largely undesirable extremes of temperature/pH conditions, within these limits lies a range of processing options that can produce a spectrum of distinctive quality attributes. A diagrammatic depiction of the range of potential processing options as they affect tenderness is shown in Fig. 1. This figure represents the 'processing space' produced from a range of possible chilling rates (x axis) and rates of pH decline (y axis). Although the rate of pH decline is itself temperature dependent, the range of pH decline rates described here depends primarily of the extent of post-mortem electrical stimulation.

The more quantitative graphs in Fig. 2 are derived from an ongoing research programme to develop a predictive meat quality model that can be used to calculate quantitative measures of meat quality outcomes – tenderness, colour, colour stability and waterbinding capacity – from any choice of processing options. The stimulation fraction

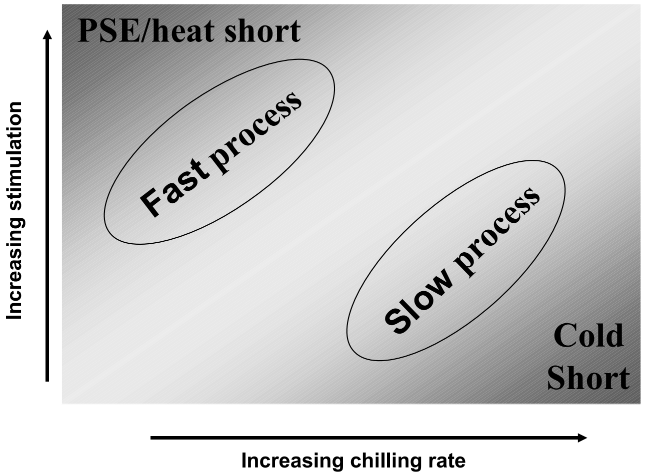

Fig. 1. Diagrammatic representation of processing options – quality outcomes resulting from modifications to rates of pH fall and cooling. (1) Fast process; rate of pH fall is rapid combined with a slow cooling rate. Slow process; rate of pH fall is slow combined with a fast cooling rate.

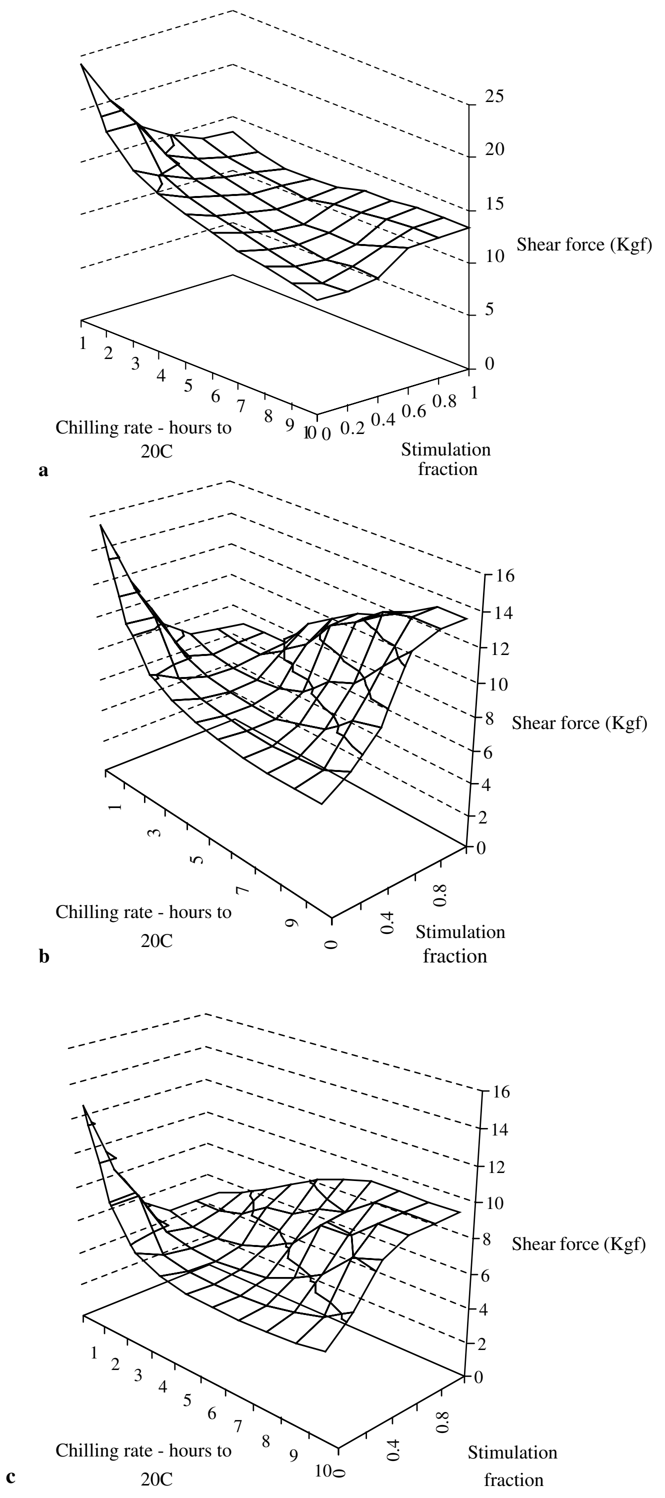

Fig. 2. Calculated tenderness values across processing space. (a) Tenderness at 24 h post-mortem; (b) tenderness at 7 days post-mortem; (c) tenderness at 14 days post-mortem. (1) Shear force measured by MIRINZ Tenderometer, in KgF; (2) stimulation fraction expressed as a proportion of maximal stimulation.

provides an indication of the level of electrical stimulation, where for example a stimulation fraction of 1.0 would represent a typical high voltage stimulation regime, while a stimulation fraction of 0.2 would be representative of minimal low voltage stimulation applied after sticking. These calculations clearly show the effects of cold shortening and denaturing conditions on tenderness values at 24 h, 7 days and 14 days post-mortem. The general principles used in this approach have been used previously (Dransfield, Jones, & MacFie, 19801981; Offer, 1991), and these are being expanded to provide a wider range of processing conditions and quality outcomes and across a wider range of quality attributes, including colour and colour stability, and waterbinding capacity.

The graphs in Fig. 2 illustrate the clear benefits of different processing options for New Zealand meats exported frozen as opposed to chilled. Once frozen, the tenderising process stops, therefore product should be allowed an appropriate period to tenderise before it is frozen; commercial efficiencies require a fast processing option, and such a specification involves slow chilling and a rapid pH decline (vigorous electrical stimulation).

What the predictive modelling illustrated in Fig. 2 helps to define is the optimum balance between a number of sometimes conflicting requirements. For example, a processor preparing meat destined for retail within a few days of slaughter or for freezing requires accelerated proteolytic activity to ensure the meat is tender when purchased or frozen. In contrast, a chilled meat exporter has the advantage of anything from two to six weeks of chilled storage during transit in which tenderisation can occur and needs product that will remain stable for these prolonged periods. In very broad terms, a process tailored for retail within a week of slaughter or freezing 1–2 days after slaughter requires a fast rigor onset consisting typically of a high level of electrical inputs to the carcass and a two stage chilling process that incorporates a period of slow cooling (high temperature conditioning). In contrast, a process tailored for a 6-week chilled product will require a slow rigor onset; typically this involves minimal electrical inputs combined with a reasonably rapid chill. Such a process will reduce the chances of excessive degradation of meat structure (overageing), minimise purge losses by avoiding muscle protein denaturation, and help to maintain colour stability after the end of the storage period.

2.1. Practical considerations in managing pH and temperature

In theory, effective control of post-mortem pH and temperature decline can provide precise management of meat quality outcomes. In practice, this can be difficult to achieve under commercial conditions. Although the chilling of a carcass can be accurately managed with controlled air temperatures and airflows, there must of necessity be significant temperature gradients between the surface and deep tissues of a carcass during the chilling phase (the gradient can be as much as 12 °C between surface and deep muscle tissue), and these gradients impose some absolute limits to effective temperature control, particularly so in large beef carcasses.

Also, the rate of pH decline is highly variable between animals, even when comparing within the same muscle. For example, we undertook to measure the rate of pH decline in 270 prime beef *Longissimus lumborum*, removed from the carcass at 20 min post-mortem and equilibrated to 15 °C until the ultimate pH was attained: under these conditions, the pH decline is linear with an average value of 0.086 pH units/h (SD 0.02), but the least and greatest rates were 0.016 and 0.389 pH units/h.

Equally, the response to electrical stimulation can also be variable. The effectiveness of low voltage stimulation can be variable, recent work (Simmons, Gilbert, & Cairney, 1997) reported a large variation in pH fall between carcasses; in some instances, the pH fall post-stimulation was equivalent to the unstimulated carcasses. In this study, we maintained samples at a constant pre-rigor temperature after stimulation and concluded that the variable responses were largely due to animal history rather than processing conditions.

2.2. Improving control of muscle chilling: the hot boning option

One solution to controlling the pre-rigor temperature gradients through a carcass is to reduce cut size and chill each independently. Processing the carcass before chilling and while the muscles are still in the pre-rigor state – a process generally referred to as hot boning – allows the whole carcass to be reduced to individual muscles or primal cuts. The small portion size creates the possibility of a more even chill, but also the introduction of additional technological options that are not available to meat chilled on the carcass.

The New Zealand meat industry has, in many respects, pioneered the commercial application of hot boning and, currently, about 20% of New Zealand beef production is processed hot. Historically, hot boning plants were used almost exclusively to process manufacturing beef from bulls and cows, but this is no longer the case: it is now commonplace to process prime beef animals using hot boning procedures. Regular audits of product quality have amply demonstrated that eating quality and other quality attributes can match those of meat produced by more conventional cold boning procedures, as long as the processing variables of pH and temperature decline are effectively managed.

2.3. Immersion chilling

Early assessments of meat quality produced by hot boning processes identified toughening and darkening of meat, but this can be attributed to poor management of the chilling rates. Instead, the potential exists to use hot boning techniques to enhance quality, and critical to this is the control of the chilling rate. One technology developed and evaluated at the MIRINZ Centre in Hamilton, New Zealand, is immersion chilling of the hot boned cuts. The use of a liquid cooling medium is inherently more efficient and produces a faster heat transfer than air. The commercial process that has developed involves vacuum packing hot boned meat and transferring the packaged cut to a system similar to the auger system used for poultry processing. The time required for the cuts to equilibrate to the water temperature is considerably quicker than the traditional air-chilling systems. Cuts are then transferred to cartons and proceed into a second chilling stage using conventional carton chillers. Product quality through this system was high, as were the operating efficiencies. Some shape deformation was evident in the larger cuts, but this could be overcome by judicious placing of formers against the cut face.

2.4. Muscle stretching and forming

The other major opportunity offered by hot boned meat is the option of manipulating the shape and to stretch the individual muscles. Because the meat is in a pre-rigor state, sarcomere lengths are not fixed by rigor cross bridges and are able to be extended by appropriate mechanical interventions. Meat is also isovolumetric, and therefore reducing the cross sectional area by applying mechanical compression perpendicular to the fibre direction will increase muscle and sarcomere length. This physical manipulation has been shown to improve tenderness, in a manner analogous to some of the carcass manipulation systems such as Tenderstretch (Ferguson et al., 1999). However, the technique of individual muscle or cut manipulation also offers additional meat quality benefits such as a reduction in drip loss and improved colour stability (Stiebling & Kanitzschky, 1997). At least two systems have been developed for commercial use: The Pi-Vac® packaging system that moulds the meat using a combination of tubes and specialised plastic film, and a second system developed by AgResearch under contract to Meat and Wool New Zealand. This latter system generates a significant stretch and increase in sarcomere length and, when combined with optimal cooling regimes, offers significant meat quality improvements. Moreover, this system can be used for upgrading low value cuts and for binding meat pieces together without artificial binders (unpublished observations).

2.5. Improving control of post-mortem muscle pH decline

The second arm of effective processing is controlling pH decline within limits defined by temperature. In addition to the inherent variability in the post-mortem pH declines in muscles, alluded to earlier, electrical inputs used during carcass processing can produce significant effects on pH decline. Examples of electrical inputs are electrical stunning, electrical immobilisation and electrical stimulation.

Head-only electrical stunning is now the standard pre-slaughter stunning procedure for both sheep and cattle in New Zealand. Much of this is in response to the requirements for Halal slaughter, which specifies that the stun should not be responsible for the death of the animals. Head-only electrical stunning meets the requirement for instantaneous and sustained loss of consciousness that allows exsanguinations to be the primary cause death. However, the epilepsy triggered by a head-only stun cause severe convulsions that need to be managed both to limit risks to operators and to maintain high throughputs.

The standard procedure used in New Zealand plants for both sheep and beef slaughter has been to follow the electrical stun with a period of electrical immobilisation during the bleeding procedure to suppress convulsive activity and thus allow the workers to safely undertake further workup on the carcass. For this purpose, an electrical current based on the standard low voltage stimulation parameters of 90 V and 10 ms pulses delivered at 15 Hz has been the normal system, as these voltages are considered sufficiently safe to allow operation without safety barriers.

This low frequency waveform has been borrowed from electrical stimulation procedures and is persisted with because it has proved effective at suppressing convulsive activity, but with little regard for the implications on pH decline in immobilised carcasses. Not surprisingly, a waveform developed for the purpose of stimulation is particularly effective at reducing muscle pH, often beyond the optimal levels for meat quality. In addition, the stimulation effect of immobilisation can interact with subsequent carcass stimulation after dressing to produce adverse effects on meat quality. Effectively suppressing post-stun convulsions while also controlling effects on pH decline are therefore important for managing meat quality during processing.

Two techniques have been developed for this purpose, both based on the selection of electrical waveform frequencies to selectively manipulate different responsive tissues. Daly (2005) recently reviewed the underlying principles of how excitable tissues respond to electrical waveforms. In brief, there are two considerations when assessing the responses of excitable tissues to an applied electrical waveform: these are the pulse duration and the pulse frequency. Reducing pulse duration increases the voltage threshold needed to trigger an action potential, but this threshold is also defined by the physical characteristic of the target cell: cells with low internal electrical resistance, primarily a consequence of large cell size (or, in the case of neurones, cell diameter) are able to respond to shorter pulses than cells with high internal resistance. Peripheral motorneurones, for this reason, have the lowest threshold. In contrast, although muscle fibres can have large diameters, the dense packing of contractile proteins produce a high internal electrical resistance and these cells have, by comparison, a much higher threshold. The consequence of these response characteristics means that appropriate choice of waveform frequencies can be used to selectively stimulate specific responsive tissues, and the use of very short pulse durations will permit stimulation of motorneurones without direct stimulation of skeletal or cardiac muscle. The electrical parameters used to produce a maximal muscle response in a whole carcass will involve pulse durations of 2–10 ms and 500–1000 peak V, while stimulation of motorneurones with minimal effects on muscle tissues can be accomplished with pulse durations around 0.1 ms and 100–200 V.

The second important attribute of the stimulation waveform is the pulse frequency. With increasing frequencies, the interval between pulses becomes less than the time needed for responsive cell membranes to recover from the induced action potential: in other words, the pulses encroach on the partial refractory period, which both fails to trigger an action potential but also delays recovery of the membrane to the responsive state. The consequence of this is that the responses of the cell to high frequency stimulation becomes intermittent and generates only a low frequency of responses. In peripheral motorneurones, with an action potential duration of, typically, around 1 ms, a reduction in muscle activation becomes particularly evident when frequencies exceed 1000 Hz, and decreases monotonically as the frequency increases above this.

The ability to manipulate independently the responses of different tissues has been exploited in two ways.

2.6. High frequency electrical stunning to provide electrical immobilisation with minimal effect on post-mortem pH decline

Electrical immobilisation after stunning plays an important role in ensuring operator safety and maintaining high throughput levels. The conventional system, based on low frequency waveforms, often results in excessive pH decline during and subsequent to the stimulation, particularly when immobilising large cattle that subsequently cool very slowly.

The use of stimulation waveforms based on short pulse durations (around 100 μs) combined with frequencies up to 2000 Hz has been found to produce effective and persistent suppression of convulsive activity while generating only marginal levels of pH decline. An objective demonstration of the effects of a high frequency immobilisation waveform compared with the conventional 15 Hz waveform is shown in Fig. 3. In these experiments, the responsiveness of sheep carcasses was measured immediately after stunning and exsanguination by hanging the carcass on a load cell. The carcass responsiveness was measured at 15 s intervals during the course of a 60 s immobilisation protocol using either 100 μs pulses at 2000 Hz or 10 ms pulses at 15 Hz. At each 15 s interval, measurements were made of the carcass response to two test stimuli; one that would trigger muscle contraction through either direct stimulation of the muscle or indirectly through the innervations of the muscle; and the other that would only elicit a response through stimulation of the peripheral nervous system. Before each pair of test pulses, the carcass stimulation was stopped for 3 s to allow full relaxation.

The results show that both the high frequency and low frequency waveforms cause a rapid loss of responsiveness to the nerve test pulse, and this reflects the loss of spontaneous physical movement in the carcass following the

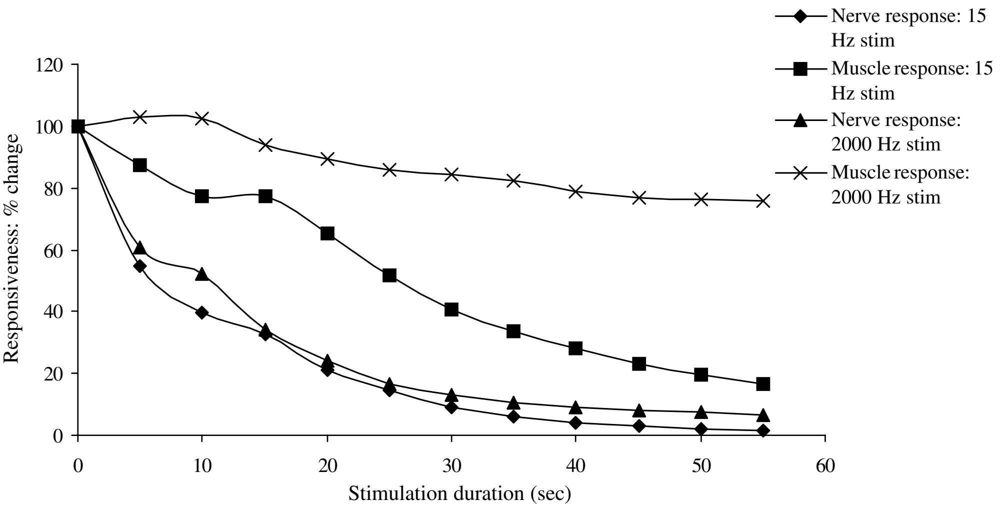

Fig. 3. Changes (%) in carcass responses to nerve tests (50 μs pulse) or muscle tests (10 ms pulse) at 5 s intervals during immobilisation using either a 2000 Hz waveform or a 15 Hz waveform. (pulse amplitudes were 1 A throughout).

immobilisation procedure. However, the responses to the muscle test pulse were distinctly different: whereas the low frequency immobilisation produced a rapid loss of responsiveness, the high frequency immobilisation produced only a marginal change. The implication is that the loss of responsiveness to the 10 msec pulses reflects muscle fatigue and an associated drop in muscle pH, and separate experiments have shown that this immobilisation protocol regularly reduces the pH of the *Longissimus thoracis et lumborum* to below 6.4. In contrast, the high frequency waveform has little effect on muscle responsiveness, and this is reflected in a muscle pH that is typically greater than 6.8.

2.7. High frequency electrical currents to suppress stun-induced convulsions without causing cardiac arrest

A key requirement of Halal slaughter is continued heart function and, for this reason, conventional electrical stunning currents that are based on 50 Hz are applied only to the head, since directing the current through the body will cause ventricular fibrillation (Gregory & Wotton, 1984). However, cardiac tissue rapidly becomes unresponsive to increasing current frequencies. Waveforms above 500 Hz require higher currents to produce ventricular fibrillation during stunning in livestock species compared with 50 Hz waveforms (Simmons, 1995), and a current 1000 Hz does not produce fibrillation even with currents exceeding 5 A through the body (unpublished observation).

The advantage of using a high frequency current in the head-to-body configuration is the effect this has on the subsequent convulsive activity. Most of the convulsive activity has its origins in the spinal cord (Esplin & Freston, 1960), and direct electrical stimulation of the thoracic region causes long lasting inhibition of convulsive activity, possibly through the release of inhibitory neurotransmitters. Even in cases where a head-to-body 50 Hz waveform induces ventricular fibrillation and systemic ischemia, it is the direct stimulation of the spinal regions that is responsible for the suppression of convulsive activity (Wotton, Anil, Whittington, & McKinstry, 1992).

We have recently developed electrical stunning procedures for both cattle and sheep that apply a high frequency electrical current (>1000 Hz) to the body in order to suppress post-stun convulsions. The initial head-only phase of the stun can be carried out with either the conventional 50 Hz waveform or one of a higher frequency, but this is then immediately followed by the high frequency head-to-body phase. In cattle, complete suppression of post-stun movement was possible with more than 10 s of high frequency head-to-body stimulation, but a level of ecchymosis was found to occur with these prolonged periods. This appeared to be caused by the complete relaxation of the body at a time when blood pressure was elevated by the stun. However, even short periods of 2–3 s are able to significantly reduce the amount of activity and it is these shorter durations that are currently being used for commercial applications. In sheep, a 2 s head-only stun followed by a further 2 s head-to-body provided effective movement control.

The benefit of using a high frequency head-to-body component during the stun is twofold: the muscle activity associated with convulsions is avoided or reduced, and the need for subsequent electrical immobilisation to provide operator safety is avoided. These effects have significant implications for the control of post-mortem pH decline, and this approach to electrical stunning provides a useful tool for effective process control.

2.8. Feedback stimulation

The specification for electrical stimulation has traditionally been defined by application to a carcass of a voltage applied for a specified time. The high voltage system developed by MIRINZ was based on generating a maximal stimulation using 1143 V peak pulses for a period of 90 s, and the pH at the end of the stimulation is typically between 6 and 6.2 (Davey & Chrystall, 1980). This approach to stimulation produces very consistent results because the stimulation is essentially maximal and the pH at which muscles lose their responsiveness is defined physiologically. However, such an extreme pH decline is appropriate for very specific market requirements: in New Zealand, the objective with this stimulation procedure is to produce accelerated aging in order to permit freezing the product within 24 h of slaughter when a reasonable level of tenderness has occurred.

An alternative to the high voltage systems is the low voltage stimulation system. Typically low voltage stimulation does not produce such a high level of pH decline during the stimulation itself and the subsequent rate of decline is generally little quicker than those measured in non-stimulated carcasses. Also, the extent of the pH during the stimulation is difficult to control by simply reducing the stimulation voltage or the duration of the stimulation, and the rate of decline following the stimulation can also be unpredictable (Simmons et al., 1997). The objective was therefore to develop a stimulation methodology that permits any intermediate target pH to be defined and attained consistently.

The basis for this new approach to electrical stimulation is to measure the response of the carcass during the stimulation and, from the nature of these responses, derive information about the pH of key muscles, particularly the *Longissimus thoracis et lumborum* muscle (LD). By repeatedly testing the state of the carcass during the stimulation process, it becomes possible to stop the stimulation when the pH has reached the designated level. To achieve this, two components are added to the normal stimulation procedure: first, load cells are mounted on the stimulation rail at intervals, to allow the response characteristics to be measured; and, second, defined test pulses are introduced into the standard 15 Hz stimulation waveform, and it is the carcass responses to these test pulses that are measured from the load cells. The interrogation of the carcass response to the test pulse is measured via the load cells and analysed in real-time. The appropriate decision regarding the requirements for subsequent stimulation levels are generated via specialised algorithms that are embedded in the control software. This new system is known commercially as Smart Stimulation.

There are circumstances when stimulation is not necessarily needed, but instead the pH needs to be monitored in order to ensure that the carcass fits within a pre-defined pH/temperature window – this would apply for example to the Meat Standards Australia (MSA) beef grading window. Under these circumstances, the smart stimulation would use the test pulses, which on there own, have a minimal effect on pH fall. This indirect pH measure can then be combined with the appropriate chiller specification and thereby provide an on-line measure of compliance to processing specification on a carcass-by-carcass basis.

An unexpected and extremely valuable component of this technology is the ability of the system to also predict ultimate pH and tenderness. Preliminary data suggests that the nature of the carcass response to the early test pulses can be analysed in such a manner that the eventual ultimate pH can be predicted – initial data shows that the accuracy of the prediction is greater than 70%, but this will be validated by the on-going commercial testing.

3. Conclusion

Managing the temperature/pH history of muscle during the pre-rigor period to avoid the risks of cold shortening and PSE has long been a recognised requirement for managing meat quality. However, even within these extremes, effective control of temperature and pH decline post-mortem offers the opportunity not only to improve product consistency but also to tailor the quality attributes to the requirements of specific markets.

Part of the requirement for processing to tightly defined specifications is to develop the necessary technologies to control temperature and pH decline. This review has outlined some of the developments in New Zealand and Australia that form part of an ongoing research and development programme that is specifically targeting technologies that will provide commercial meat processors with the ability to increase control over meat quality outcomes.

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